

USM3D Predictions of Supersonic Nozzle Flow

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Outline

- Introduction
- Experimental Data
- Computational Methods
- Grid Generation
- Results
 - Seiner Supersonic nozzle
 - Putnam Supersonic nozzle
- Summary

Introduction

NASA Fundamental Aerodynamics Program High-Speed Project High Fidelity Analysis and Validation Element

Objective:

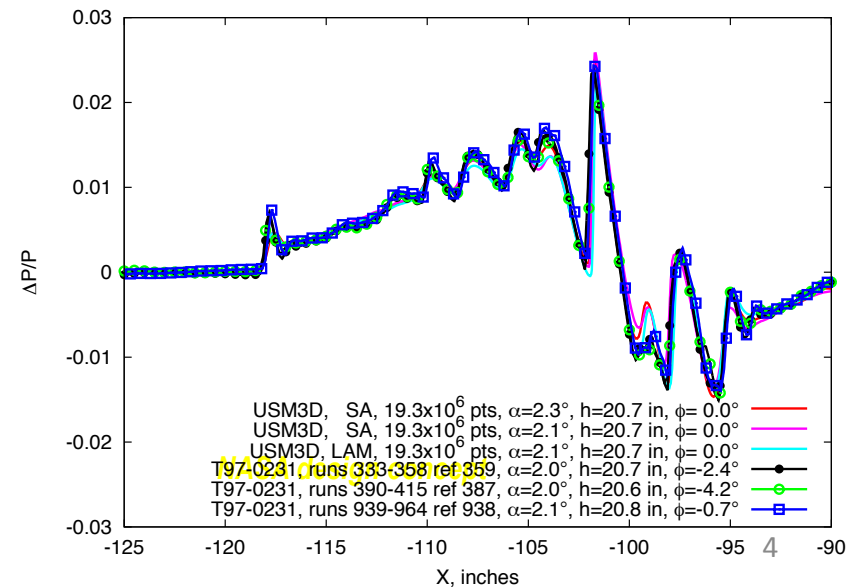
To improve aerodynamic design and analysis capability for highly efficient, supersonic vehicles

Challenges:

To develop robust CFD-based methods for rapid design and analysis of supersonic cruise aircraft that are highly efficient, and have a low sonic boom

Introduction, Cont.

- NASA High Speed Project is focusing on technologies to enable future civilian aircraft to fly efficiently with reduced sonic boom, engine and aircraft noise, and emissions.
- One major objective is improvement of both computational and experimental capabilities for design and analysis of low boom aircraft.
- **The focus of this study is to assess capability of USM3D to accurately capture exhaust nozzle flow.**



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Experimental Data

- Two benchmark, axisymmetric supersonic convergent divergent nozzles.

- **Seiner Supersonic Nozzle**

$$Mach_{jet} = 2, NPR = 7.82$$

$$Mach_{jet} = 2, NPR = 11.3$$

Reynolds number of 1.3×10^6 based on model exit diameter.

Seiner, J. M.; Dash, S. M.; and Wolf, D. E.: "Analysis of Turbulent Underexpanded Jets, Part II: Shock Noise Features Using SCIPVIS." AIAA J., vol. 23, no. 5, May 1985, pp. 669–677.

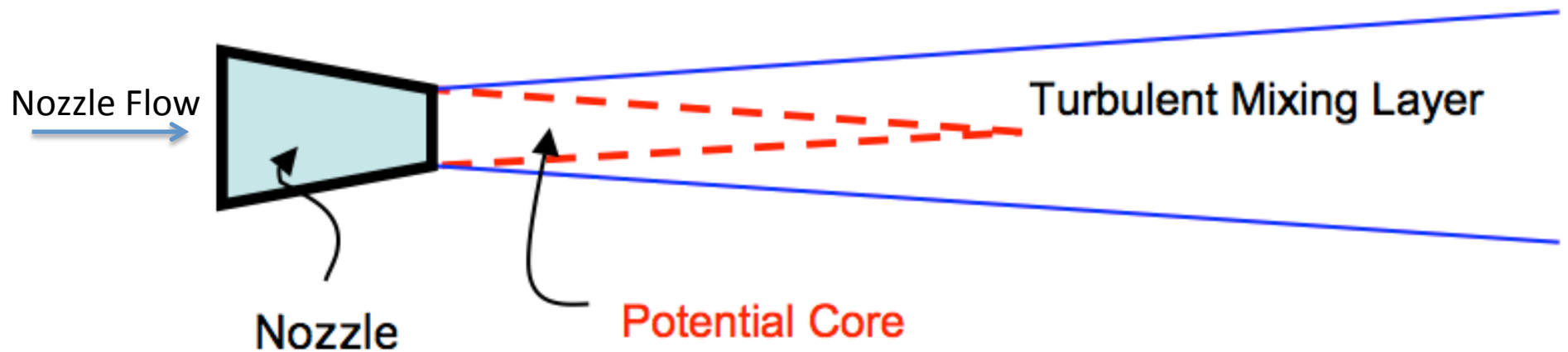
- **Putnam Supersonic Nozzle**

$$Mach_{jet} = 2.2, NPR = 8.12$$

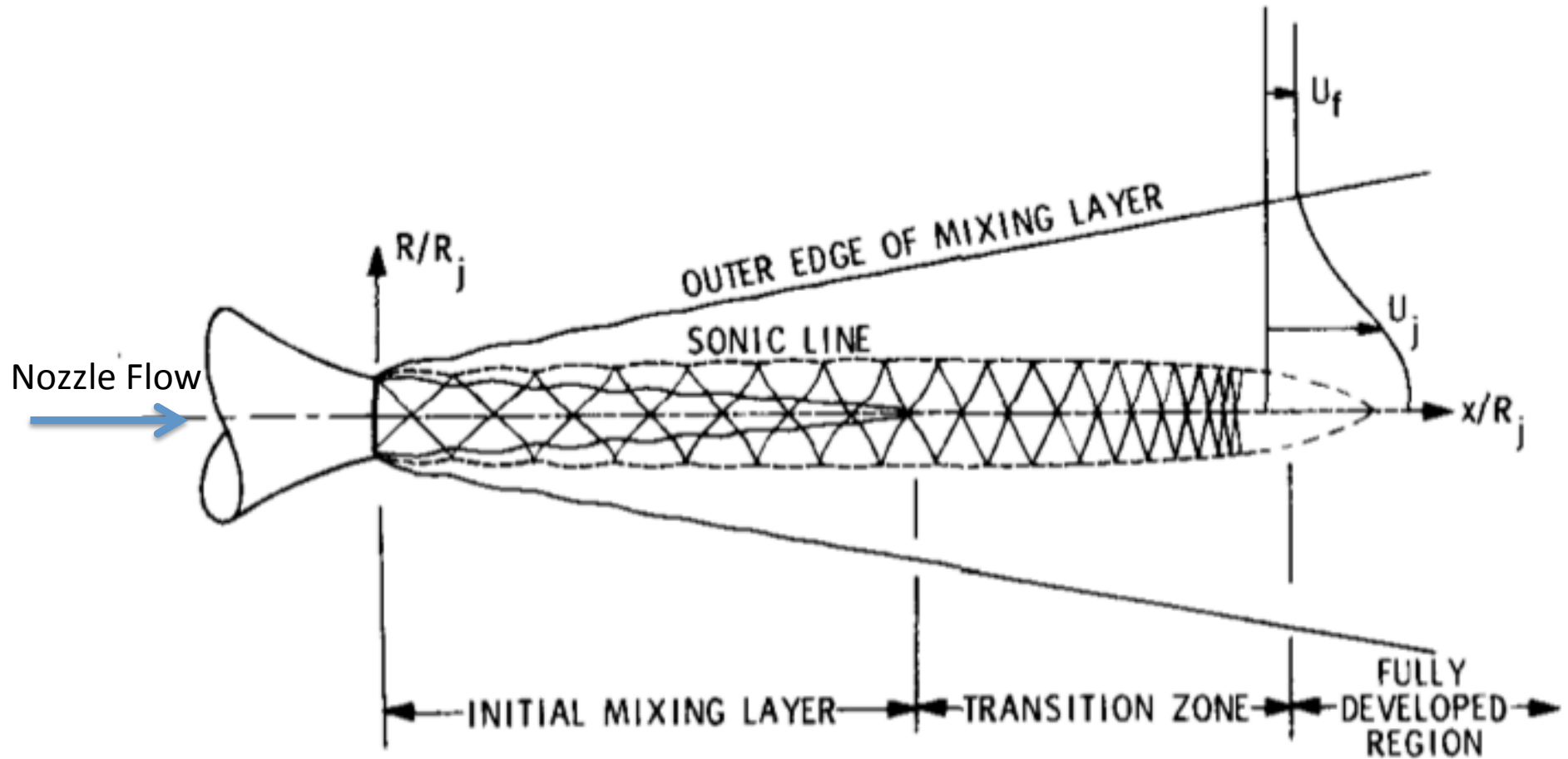
Reynolds number of 1.86×10^6 based on model maximum diameter.

Putnam, L. E. and Capone, F. J., "Experimental Determination of Equivalent Solid Bodies to Represent Jets Exhausting into a Mach 2.20 External Stream." NASA-TN-D-5553, Dec. 1969.

Typical Nozzle Flow



Under-Expanded Supersonic Nozzle Flow



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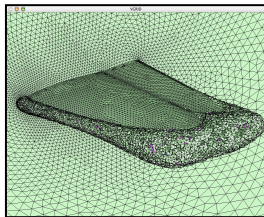


TetrUSS Tetrahedral Unstructured Software System

A proven, stable, and reliable multi-platform system for unstructured Euler and Navier-Stokes CFD analysis.



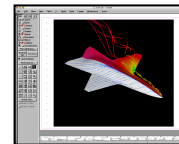
Geometry Setup
GridTool



Grid Generation
VGRID OpenGL



Flow Solver
USM3D



Visualization
SimpleView
(Commercial Packages)



Tools & Utilities

- *Complete flow analysis system*
- *Well developed infrastructure*
- *In-house experts*
- *Broad outside collaborations*
- *Design via. CDISC/SUSIE*
- *Workhorse system with large experience/confidence base*

USM3D Tetrahedral Flow Solver

- Tetrahedral Cell-Centered, Finite Volume
- Euler and Navier-Stokes
- Time Integration
 - LTS and 2nd order time stepping
- Upwind Spatial Discretization
 - FDS, AUSM, HLLC, LDFSS, FVS
 - Min-mod limiter
- Standard and Special BC's
- Turbulence Models SA, SST, k- ϵ Sarkar PD turbulence model

Computational Tools

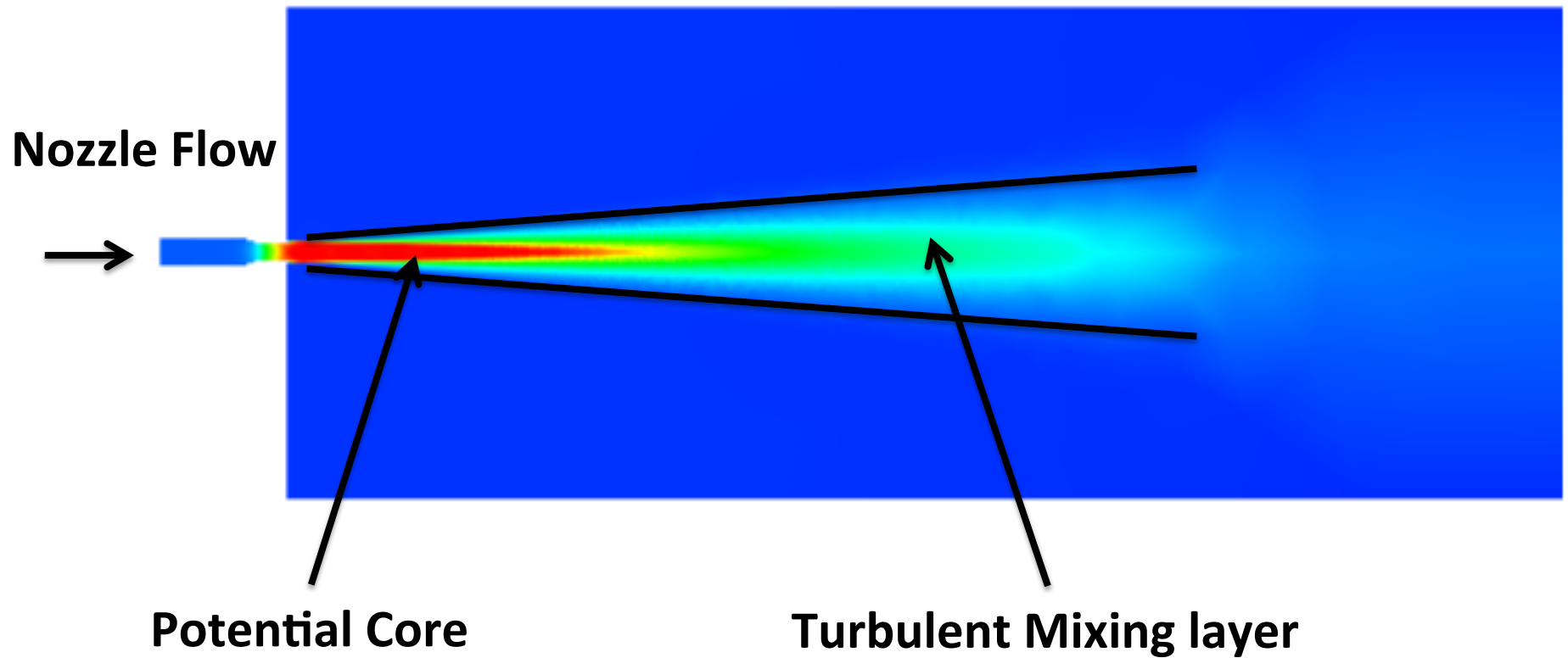
- **FUN3D**

- Unstructured finite-volume code.
- Implicit point-iterative method
- Adjoint-Based grid adaptation
- S-A turbulence model.

- **Wind-US 2**

- Structured multi-zone compressible code
- Implicit time stepping
- Modified second-order Roe upwind scheme
- Shear Stress Transport turbulence model.

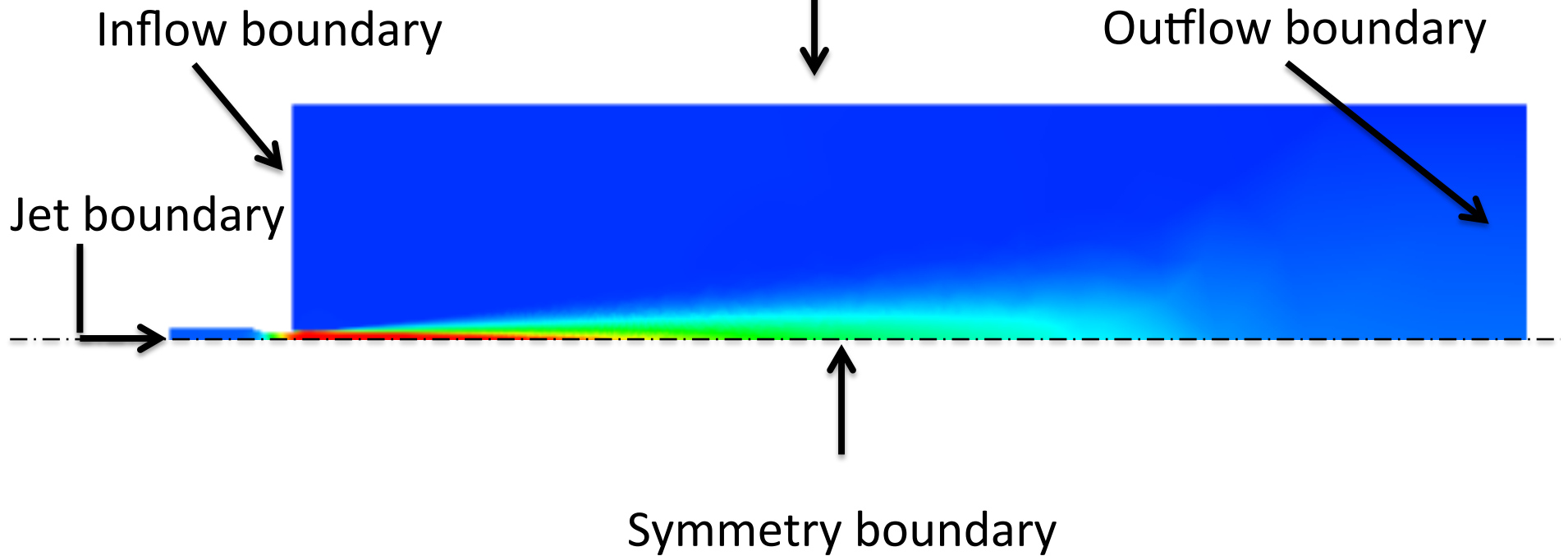
Schematic of Nozzle Flow



Boundary Conditions

10° axi-symmetric Slice

Characteristic boundary



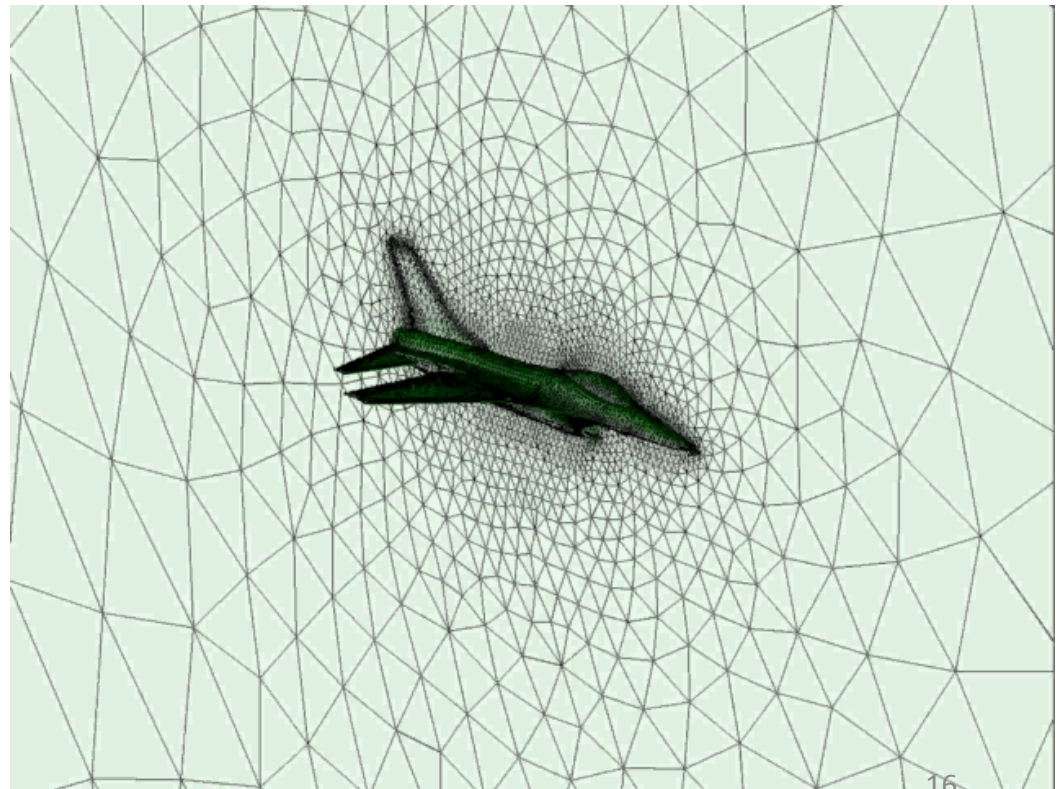
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Grid Methodology

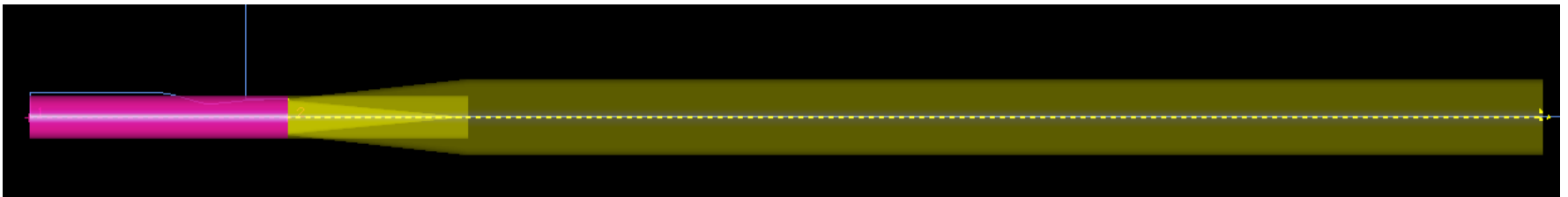
- Unstructured grid generation software: VGRID
 - Advancing front, advancing layers tetrahedral grid generator

Inviscid grid generation on F-16

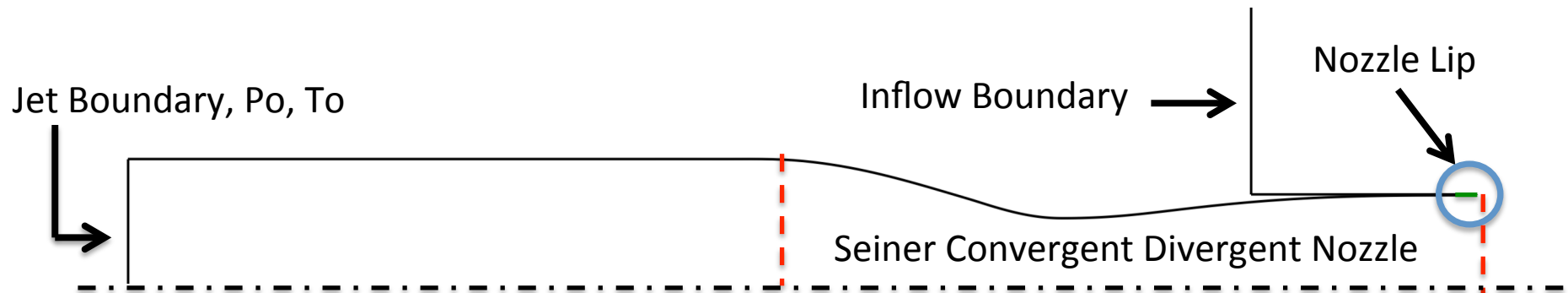


Grid Methodology

- Unstructured grid generation software: VGRID
 - Advancing front, advancing layers tetrahedral grid generator
- Five volume cylinder sources and one line source.

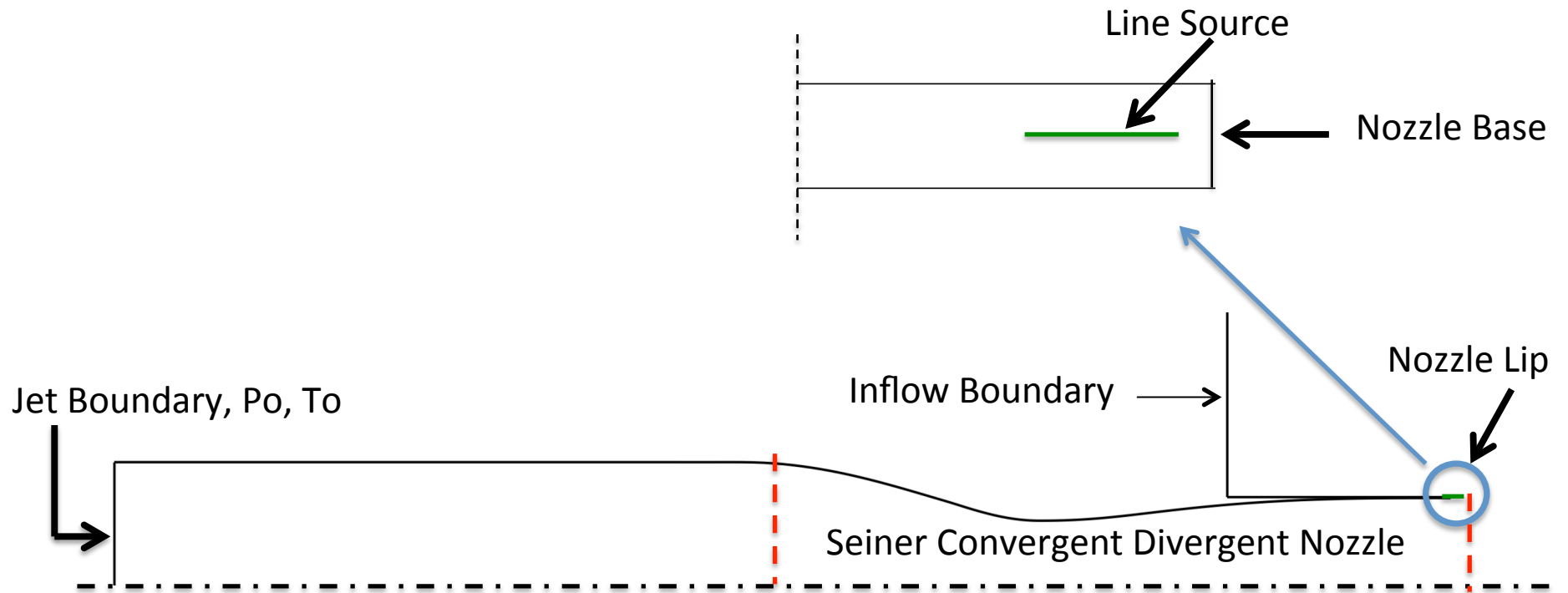


Layout for the Seiner Nozzle *Line Source*

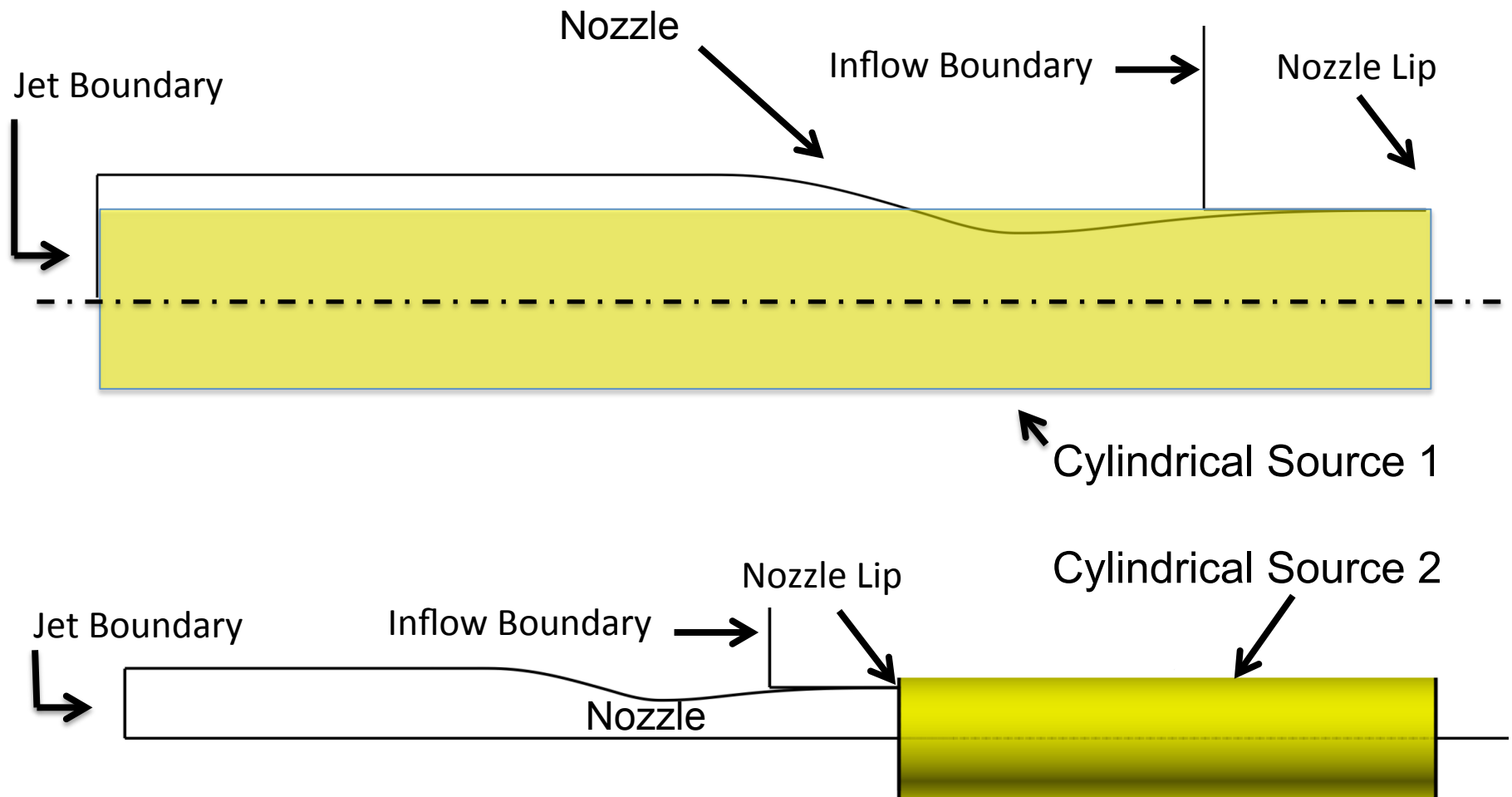


Layout for the Seiner Nozzle

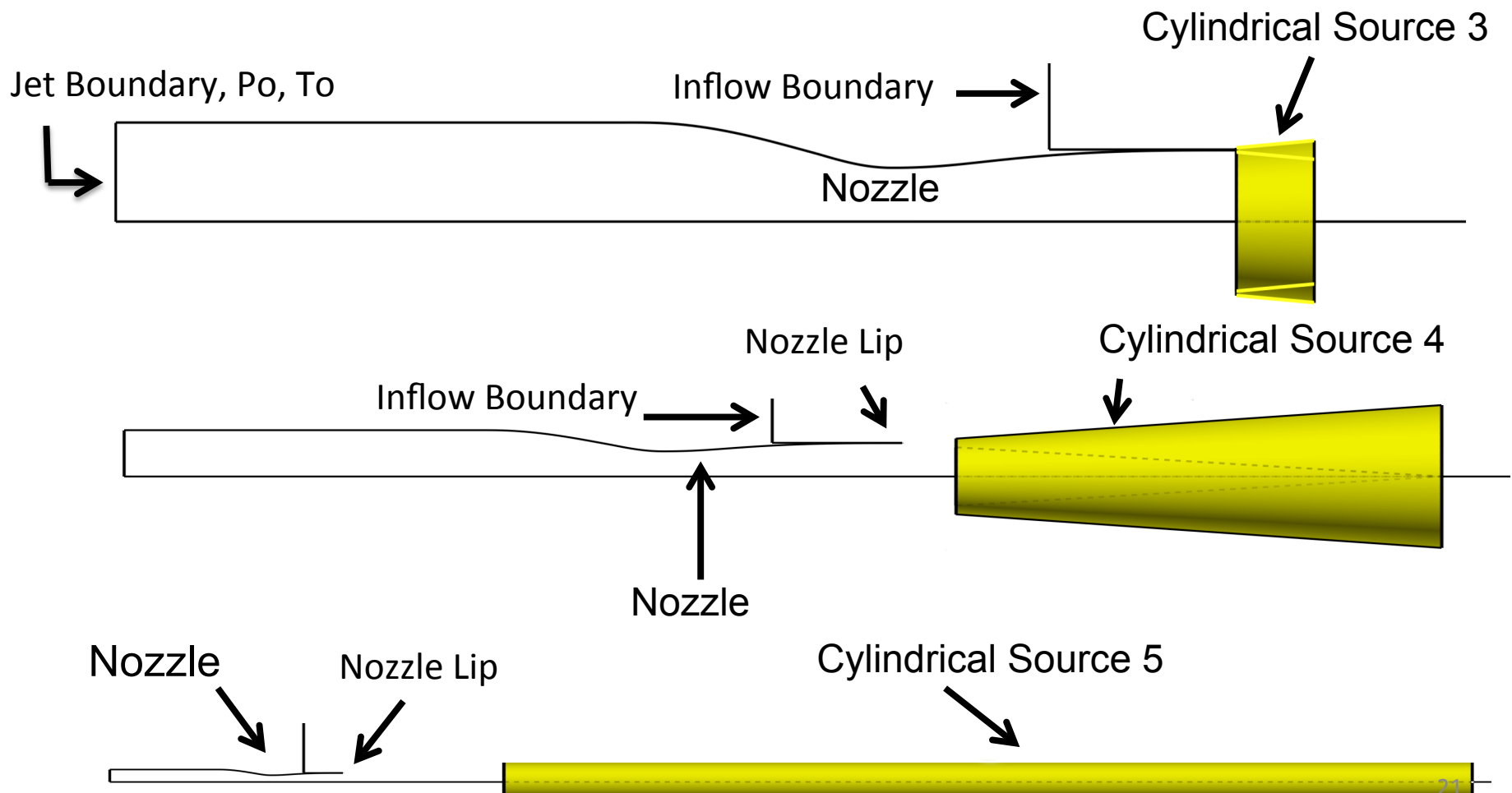
Line Source



Volume Sourcing for the Seiner Nozzle



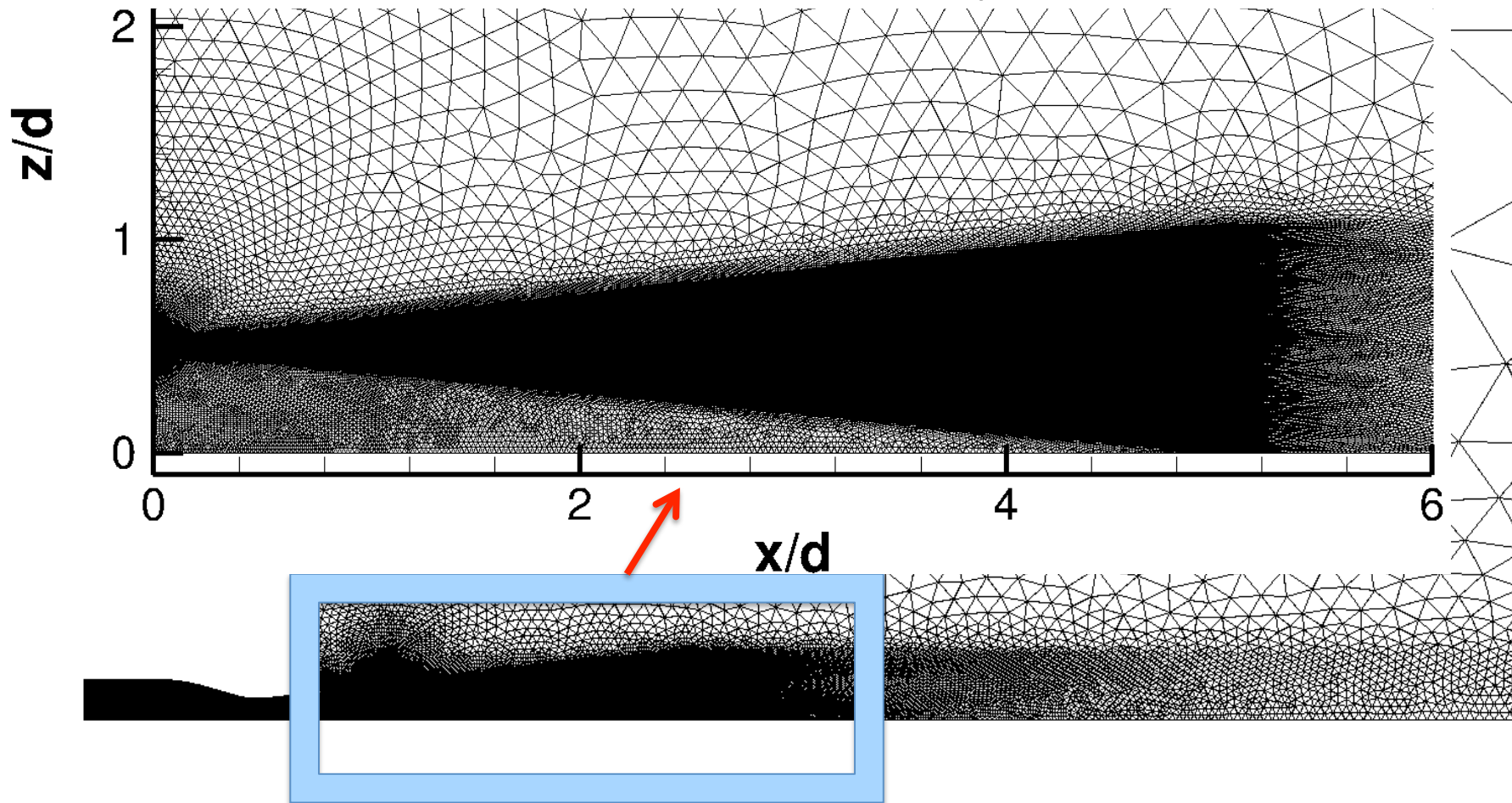
Volume Sourcing for the Seiner nozzle



Seiner Nozzle Computational Grid

Symmetry Plane

814,145 Grid Cells, 10° axi-symmetric Slice

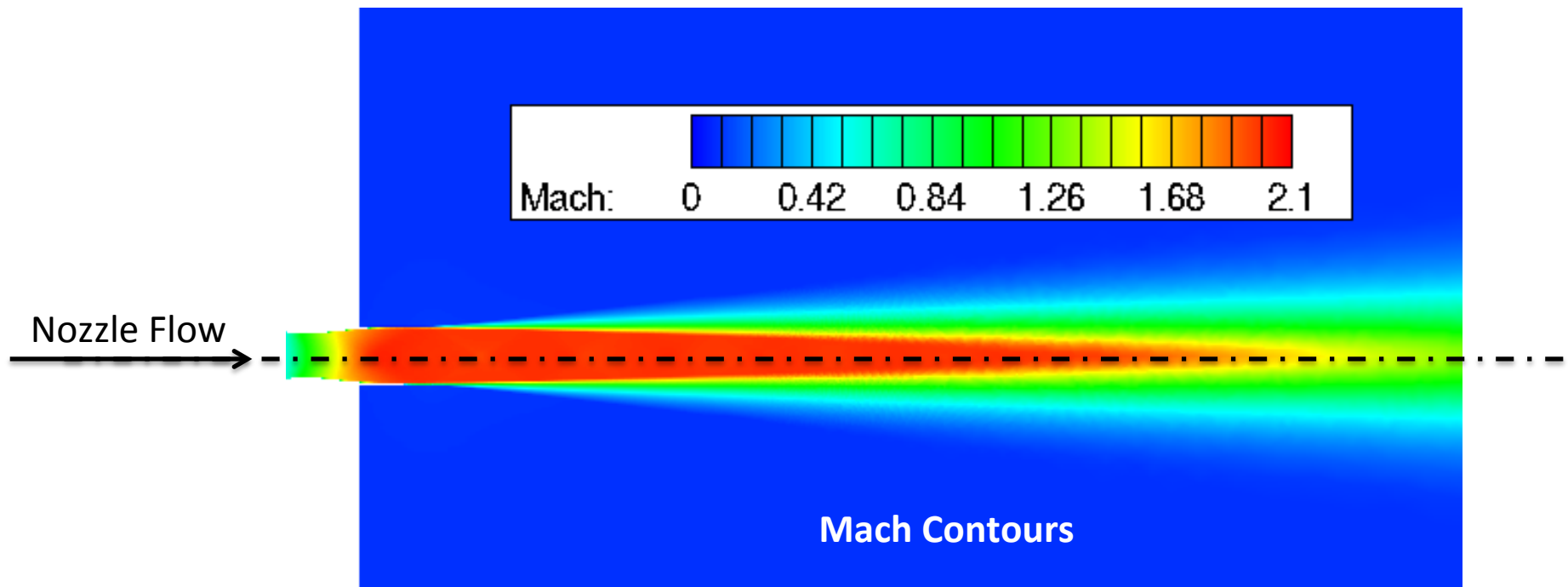


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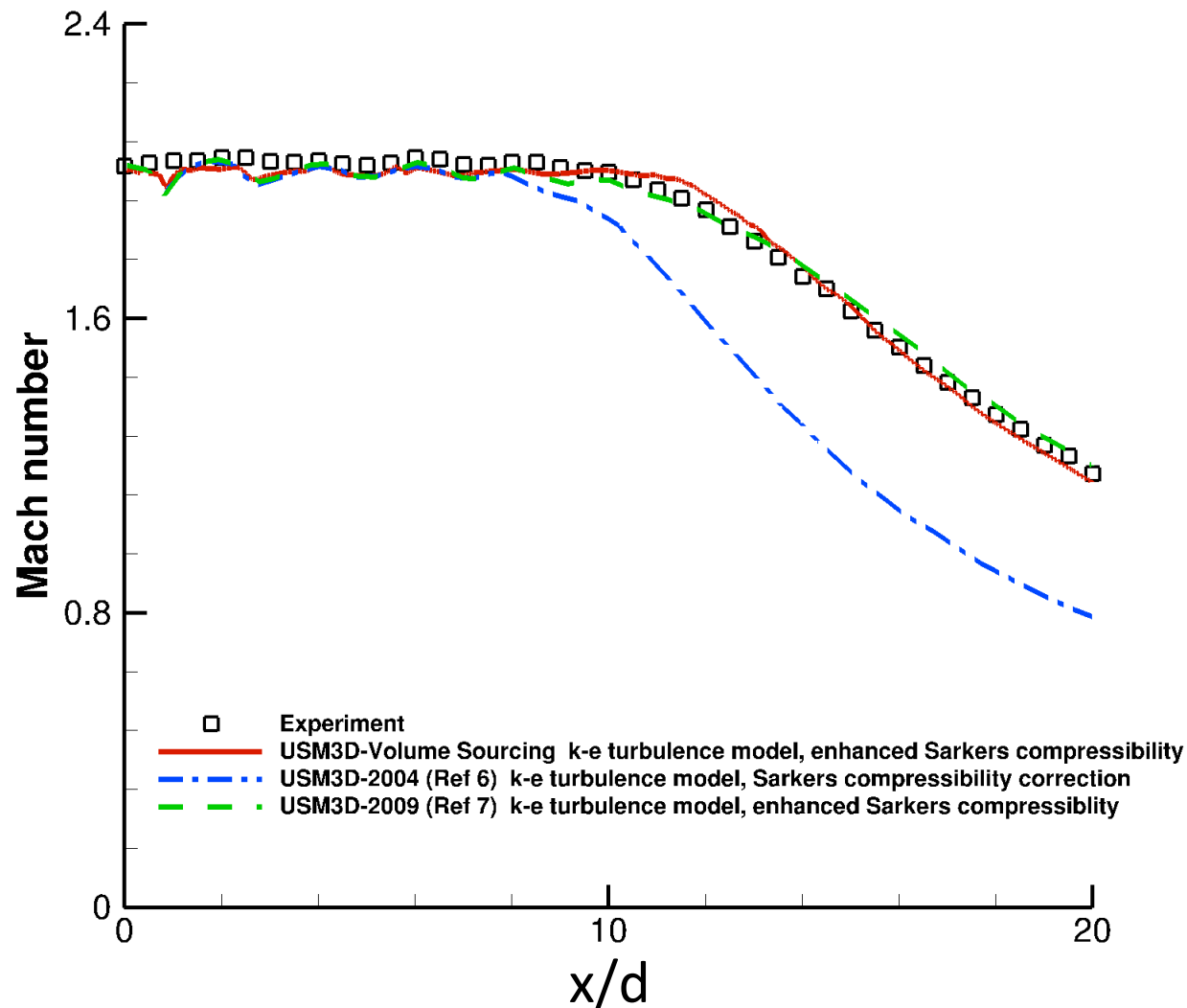
USM3D Seiner Nozzle Flow Calculations

$Mach_{jet} = 2$, On-Design NPR = 7.82, $Re = 1.3 \times 10^6$



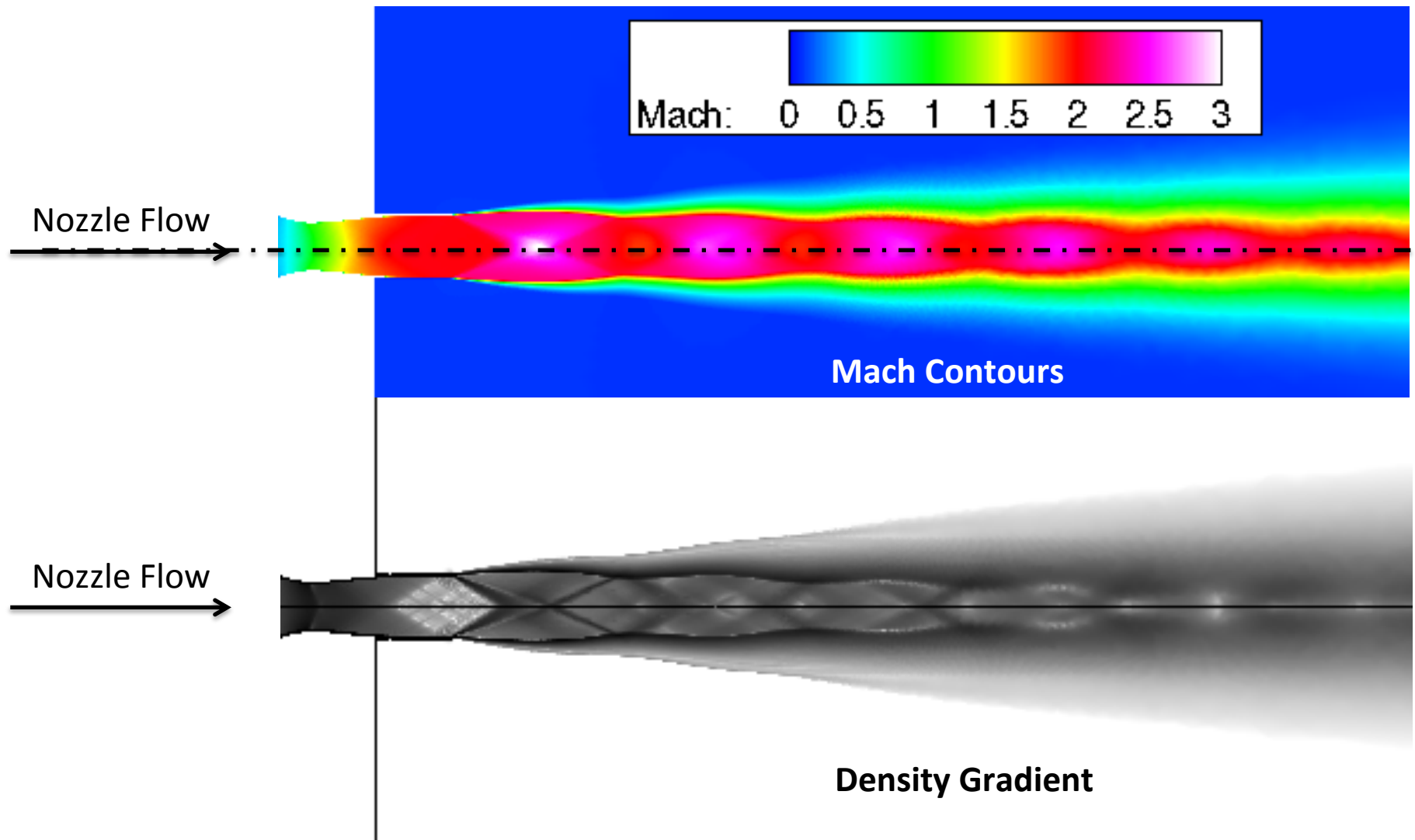
Comparison of Computed Mach Profiles with Experimental Data

$Mach_{jet} = 2$, On-Design NPR = 7.82, $Re = 1.3 \times 10^6$



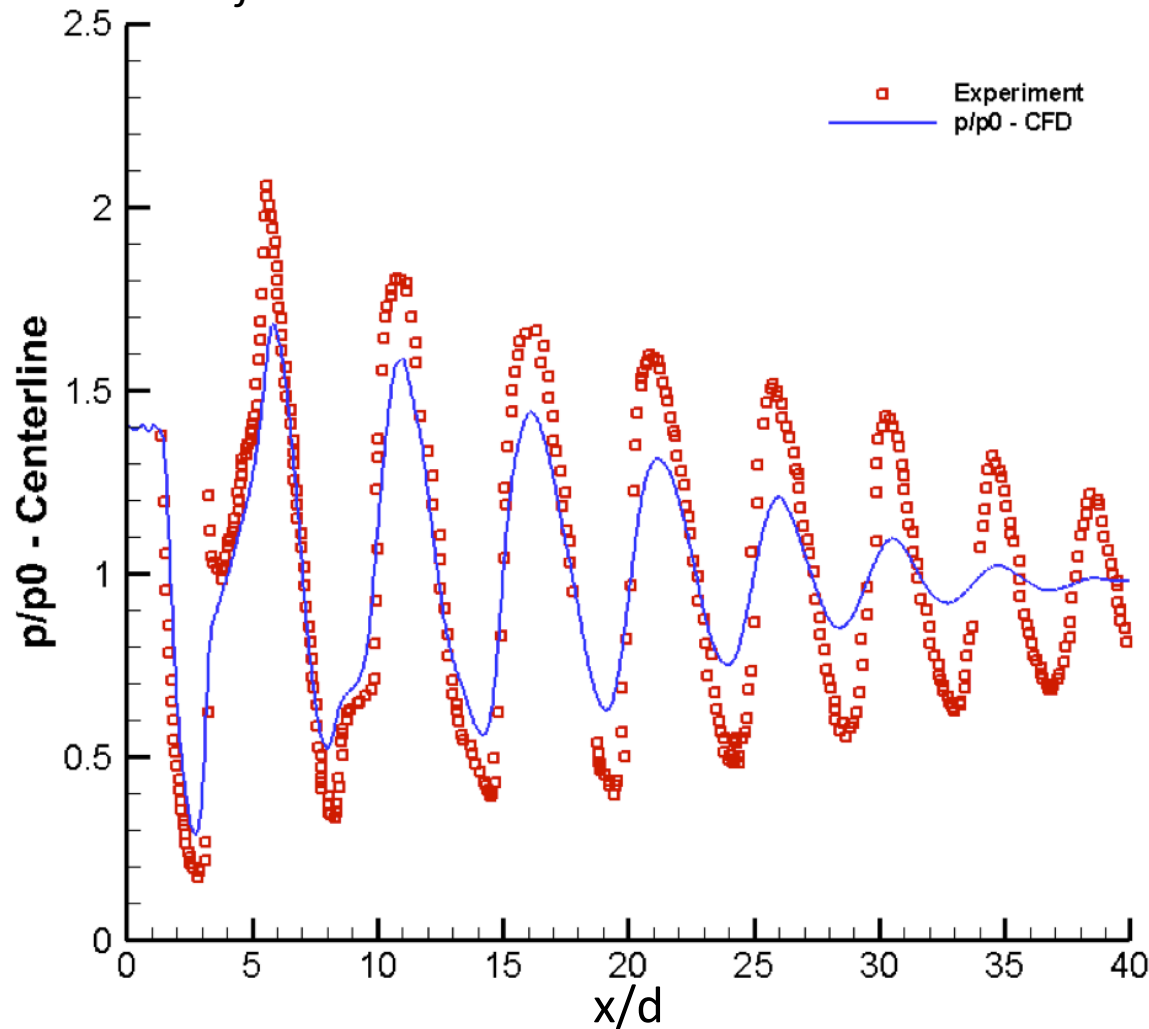
USM3D Under Expanded Seiner Nozzle Flow Calculations

$$Mach_{jet} = 2, NPR = 11.3, Re = 1.3 \times 10^6$$



Comparison of Computed Pressure Profiles for Under-Expanded Seiner Nozzle with Experimental Data

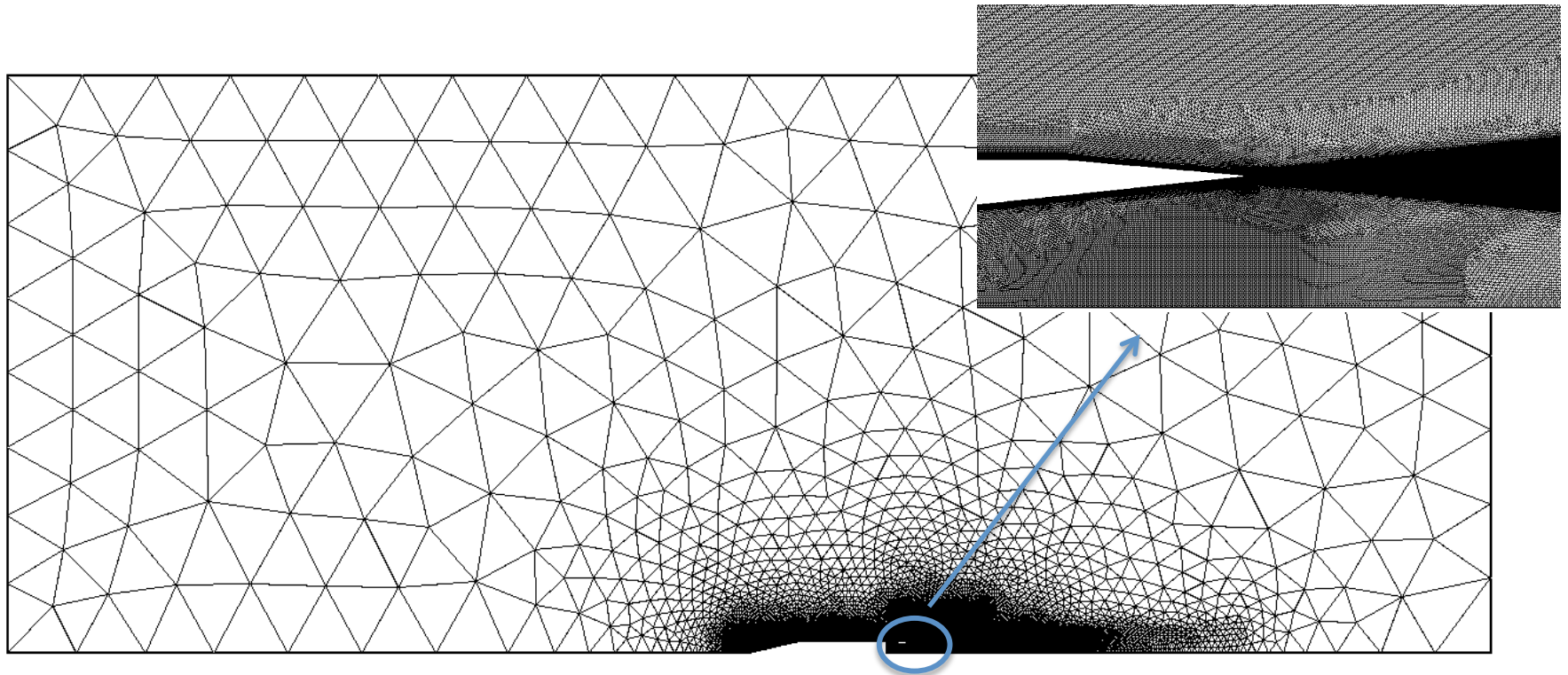
$Mach_{jet} = 2$, $NPR = 11.3$, $Re = 1.3 \times 10^6$



Putnam Nozzle Computational Grid

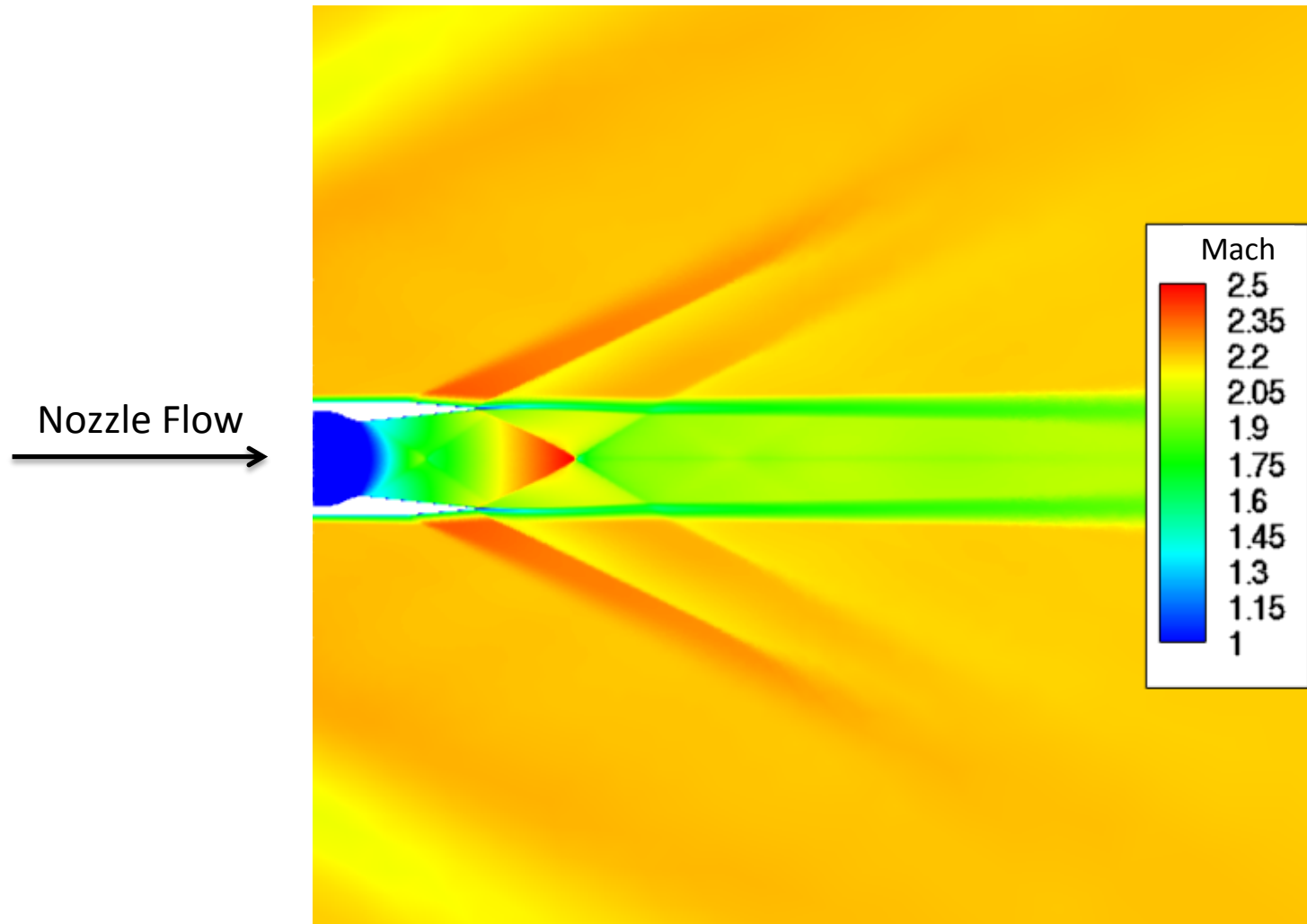
$Mach_{jet} = 2.0$, $M_{\infty} = 2.2$, $NPR = 8.12$, $Re = 1.86 \times 10^6$

1,259,430 grid cells, 10° axi-symmetric Slice



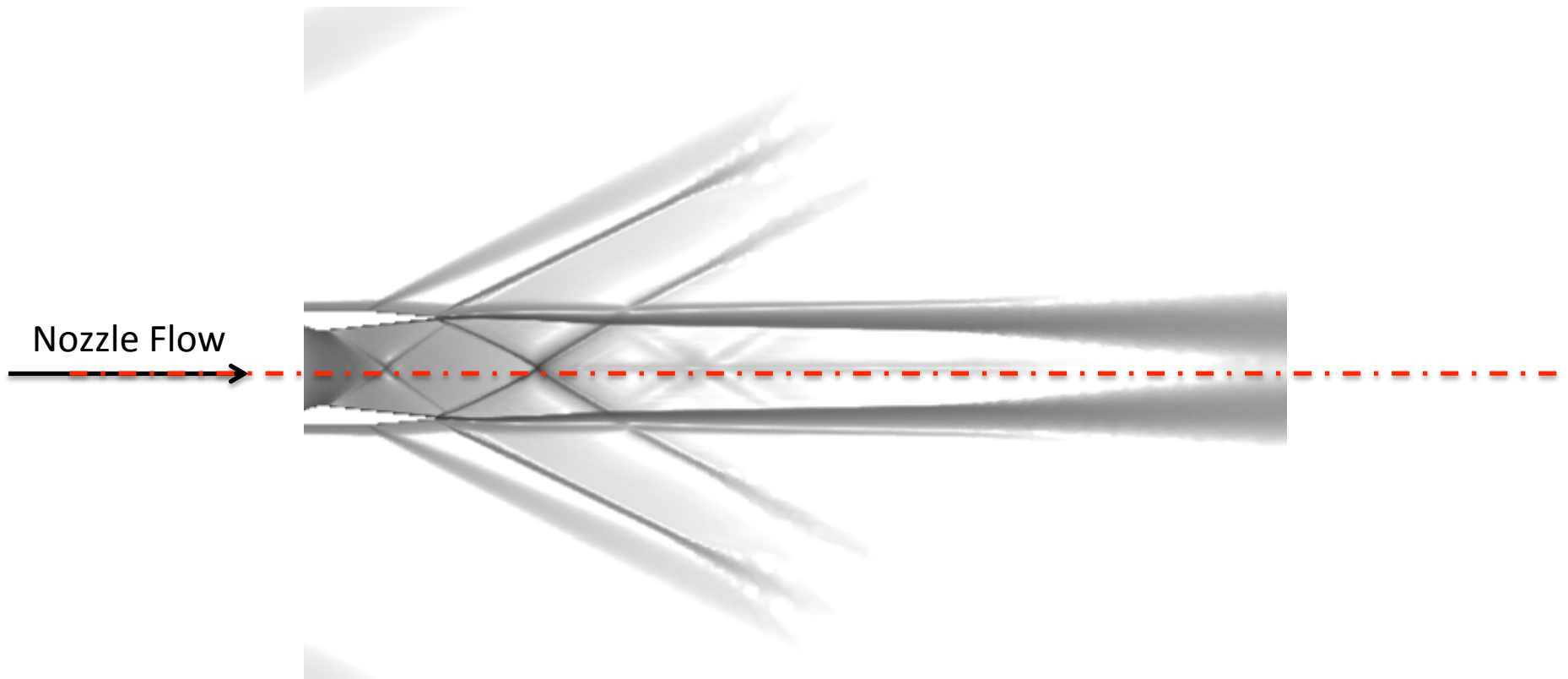
Putnam Nozzle Mach Contours

$$Mach_{jet} = 2.0, M_{\infty} = 2.2, NPR = 8.12, Re = 1.86 \times 10^6$$



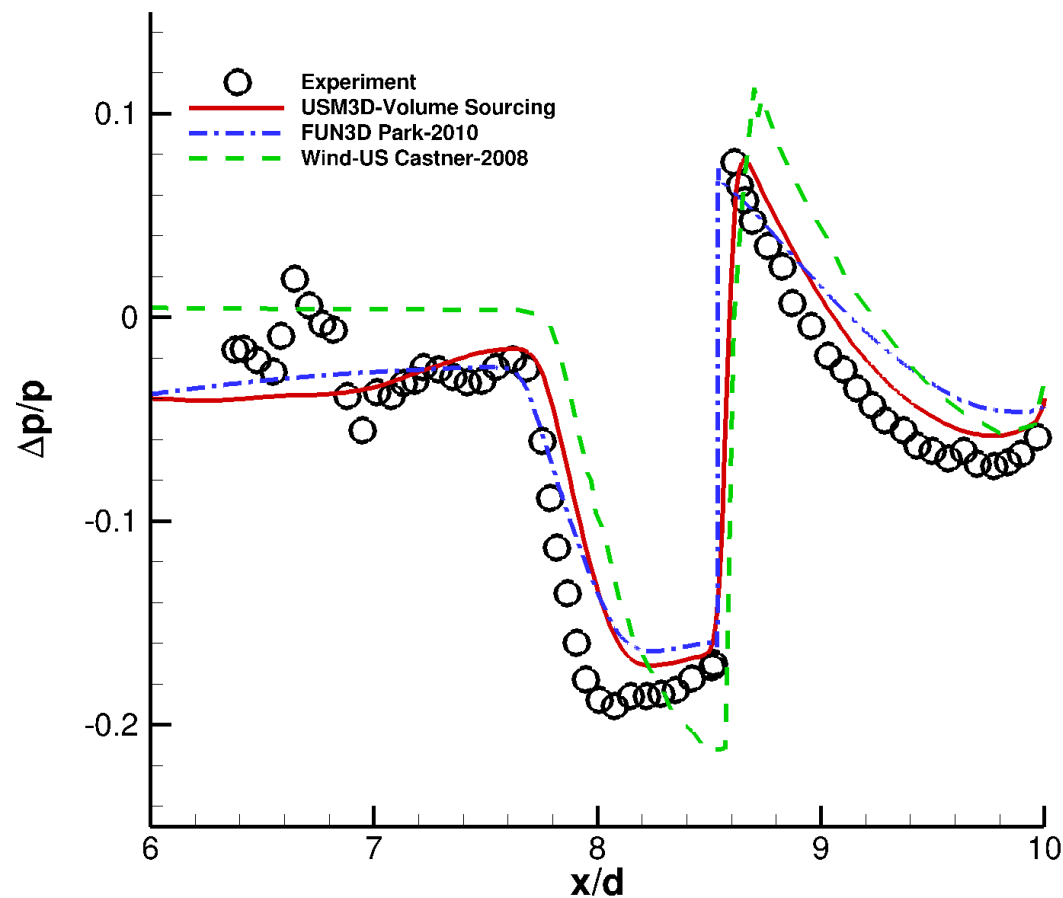
Contours of Density Gradient

$$Mach_{jet} = 2.0, M_{\infty} = 2.2, NPR = 8.12, Re = 1.86 \times 10^6$$



Comparison of Putnam Nozzle Computed Pressure Profiles with Experimental Data

$Mach_{jet} = 2.0$, $M_{\infty} = 2.2$, $NPR = 8.12$, $Re = 1.86 \times 10^6$



Summary

- USM3D was used to compute the supersonic nozzle jet flow.
 - Seiner nozzle, $Mach_{jet} = 2$, $NPR = 7.82$, $Re = 1.3 \times 10^6$
 - Seiner nozzle, $Mach_{jet} = 2$, $NPR = 11.3$, $Re = 1.3 \times 10^6$
 - Putnam nozzle, $Mach_{jet} = 2.2$, $NPR = 8.12$, $Re = 1.86 \times 10^6$
- **Grid sourcing feature of VGRID provided USM3D with the capability to resolve the jet's plume shear layer and internal shock structure.**
- Adequate grid resolution of the nozzle lip is a key factor to capture the shear layer.
- Adequate cell density is key factor to capture the core length and the shock diamonds.

Future Work

- Effect of plume and shock interaction on sonic boom signature. Wind tunnel test in 1-foot by 1-foot Supersonic Wind Tunnel at NASA Glenn.
 - Raymond Castner, Susan Cliff, Alaa Elmiligui, and Courtney Winski, “Plume and Shock Interaction Effects on Sonic Boom in the 1-foot by 1-foot Supersonic Wind Tunnel.” Abstract Submitted to the AIAA SciTech 2015.
 - Melissa B. Carter, Alaa A. Elmiligui, Sudheer N. Nayani, Raymond Castner, Walter E. Bruce, “A Computational and Experimental Study of Supersonic Nozzle Flow and Shock Interactions.” Abstract Submitted to the AIAA SciTech 2015.

Questions ?

